



## The diverse applications of water hyacinth with main focus on sustainable energy and production for new era: An overview

Shahabaldin Rezanian<sup>a</sup>, Mohanadoss Ponraj<sup>a,\*</sup>, Mohd Fadhil Md Din<sup>a,\*</sup>,  
Ahmad Rahman Songip<sup>b</sup>, Fadzlin Md Sairan<sup>a</sup>, Shreeshivadasan Chelliapan<sup>a</sup>

<sup>a</sup> Institute of Environmental and Water Resources Management (IPASA), Water Research Alliance, Department of Environmental Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia

<sup>b</sup> Malaysia–Japan International Institute of Technology, Universiti Teknologi Malaysia Kuala Lumpur, Jalan Semarak, 54100 Kuala Lumpur, Malaysia

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### ABSTRACT

Water hyacinth was introduced as an ornamental crop in many countries more than a century ago, due to its attractive appearance and aesthetical value in the environment. Unfortunately, the flowers developed into invasive species due to their adaptability for a wide range of fresh water ecosystems and their interference with human activities. In the 21st century, they were considered as an alternative to fossil fuels, as many researchers found them capable of converting their content into fuel energy at less cost and recognized as an eco-friendly product. As water hyacinth is among the group of fastest growing plants, its biomass has the potential to become a potential renewable energy source and replace conventional fossil fuels, perhaps during the next decade. This is an essential mission to overcome the depletion of energy sources and also to fulfill the increasing demand of world energy. Instead of fuel energy, the dried biomass can also be fabricated as briquettes, which is suitable as co-firing agent in coal power plant. Thus, in future compacted biomass residues produced in the form of briquettes may decrease the dependence of coal to provide more energy. The other application of water hyacinth into a co-compost material such as soil amendment to the sandy soil, can improve hydro-physical, chemical parameters of soil and will supply the growing crops with several nutrients. Water hyacinth has also drawn attention due to its bioremediation ability, capable of removing pollutants from domestic and industrial waste water effluents. Thus, the issue of water hyacinth should be evaluated from energy, engineering as well as environmental perspectives. In this review, the potential uses of water hyacinth are being classified and discussed.

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\* Corresponding authors. Tel.: +60 143149291.

E-mail addresses: [goldking1977@gmail.com](mailto:goldking1977@gmail.com) (M. Ponraj), [mfadhil@utm.my](mailto:mfadhil@utm.my) (M.F.M. Din).

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## 1. Introduction

Water hyacinth (*Eichhornia crassipes*) is a noxious weed that has attracted worldwide attention due to its fast spread and crowded growth, which leads to serious problems in navigation, irrigation, and power generation. It is also renowned as a non-native, invasive and free-floating aquatic macrophyte. Moreover, water hyacinth due to their abundant and uncontrolled growth in open pond, irrigation and other water bodies, are frequently noted in the literature as one of the world's most problematic weeds [1]. It is a free floating aquatic plant well known for its production abilities and exclusion of pollutants from water. It is able to rapidly grow to very high density of (over 60 kg/m<sup>2</sup>); this means entire clogging of water bodies can occur, which in turn may have unfavorable effects on the environment, human health and economic development [2–4].

The shoot system covers the surface of water body to capture the sunlight thereby obstructing the entry of sunlight into water, which is required by algae and other organisms present in the water to survive. This leads to a reduction in the growth of algal population and thus disturbs the ecological balance [5]. The mature plant consist of long, pendant roots, rhizomes, stolons, leaves, inflorescences and fruit clusters. The plants are up to 1 m high although; 40 cm is the usual measured height. The inflorescence allows 6–10 lily-like flowers, each one being 4–7 cm in diameter. The stems and leaves contain air-filled tissue which provides the plant its substantial buoyancy. The vegetation reproduction is asexual and takes place at a rapid rate under superior conditions [6]. It can tolerate drought conditions well because it can survive in moist sediments up to several months [7]. At an average the annual productivity of 50 kg/m<sup>2</sup> dry water hyacinth (ash-free) is in tones per hectare per year [8] and water hyacinth is one of the most productive plants in the world [2]. It can double its size within five days and a mat of medium sized plants may contain two million plants per hectare and can weigh approximately 270–400 t. Also [9] investigated that the growth rate of water hyacinth under favorable conditions can reach up to 17.5 metric tons per hectare per day. These figures also indicate that the plant may interfere with the localized problems, such as navigation, recreation, irrigation, and power generation [10].

The water hyacinth replicates sexually by seeds and vegetatively with the help of budding and stolen production. For rapid spreading, the vegetative promulgation is more important [11]. Daughter plants grow from the stolons and the doubling times have been reported of about 6–18 days. Under favorable conditions of temperature and nutrient availability, the vegetative propagation is very fast. There are seven species of water hyacinth available including: *E. azurea* – anchored water hyacinth, *E. crassipes* – common water hyacinth, *E. diversifolia* – variable leaf water hyacinth, *E. paniculata* – Brazilian water hyacinth. Clonal plants such as *E. crassipes* might enhance light interception via horizontal growth of stolons or rhizomes and a situation of new ramets, in less shaded microsites [12]. Water hyacinth is successful owing to their life cycle and survival strategy that gives it a competitive edge over other species. Its adaptability at various ecological conditions makes obliteration of this plant virtually impossible [13].

The plant has black, tough roots and when it irregularly becomes stranded in sludge it may appear rooted. Its growth rate is amongst

the highest of any plant known, and its population can double in as low as 12 days [14]. A study in Louisiana in 1948, showed that ten plants were able to vegetatively replicate 1610 plants in three months [15] also the growth rate has been calculated in other countries to be an increase in biomass of 400–700 t per hectare per day, or an increase in water area coverage by a factor of 1.012–1.077 per day. Surroundings for water hyacinth have ranged from low temporary ponds, marshes and sluggish flowing waters to large lakes, rivers and reservoirs [1].

The water hyacinth plants can withstand both high acidic and alkaline conditions, but more effervescent growth is supported by neutral water bodies [1]. As assumed by Aquatic Ecosystem Restoration Foundation [16] there is a logistic growth model in the analysis of water hyacinth population dynamics at temperate and tropical zones. Their results revealed that the growth rate in temperate regions differ with seasons. In tropical zones the intrinsic rate of growth for the weed was estimated in the range 0.04–0.08 dry weight per m<sup>2</sup> per day. It grows over a wide variety of wetland types and prefers nutrient-enriched waters. However, it can tolerate considerable variation in nutrients, temperature and pH levels. The optimum pH for growth of water hyacinth is 6–8. It can grow in wide range of temperatures ranging from 10 to 40 °C (optimum growth at 25–27.5 °C) but it is also thought to be cold-sensitive [17]. Salinity is the main obstacle for the growth of water hyacinth in coastal areas [18]. High level of salinity in wastewater can limit the growth of water hyacinth and other aquatic macrophytes [19]. Research performed by De Casabianca et al. [20] showed that water hyacinth would tolerate salinity at less than 10 ppt. In rural areas, water hyacinth could be used as an integrated approach for decentralized wastewater treatment systems coupled to biogas and compost production from the consequential biomass production [8].

Water hyacinth harvests have been put into different valuable uses in several countries. Methods of converting the plant material into valuable products have emerged [19]. This review paper highlights water hyacinth function with the ultimate attention on its utilization for energy and engineering fields conducted in the last three decades. Based on these noteworthy research realizations it is desirable to recognize as an administration strategy to adjust in the commercial activities.

## 2. Characteristics of water hyacinth

Fresh plant of water hyacinth contains 95.5% moisture, 0.04% nitrogen, 1.0% ash, 0.06% P<sub>2</sub>O<sub>5</sub>, 0.20% K<sub>2</sub>O and 3.5% organic matter. On zero-moisture basis, it has 75.8% organic matter, 1.5% nitrogen and 24.2% ash. The ash contains 28.7% K<sub>2</sub>O, 1.8% Na<sub>2</sub>O, 12.8% CaO, 21.0% Cl, and 7.0% P<sub>2</sub>O<sub>5</sub>. The crude protein (crude protein=amount of nitrogen × 6.25) using Kjeldahl method contains, per 100 g, 0.72 g methionine, 4.72 g phenylalanine, 4.32 g threonine, 5.34 g lysine, 4.32 g isoleucine, 0.27 g valine, and 7.2 g leucine [21].

## 3. Application of water hyacinth

Water hyacinth consisting of high percentage of water, fibrous tissue, high energy and protein content can be used for a variety of useful applications. A number of possible uses of the plant

includes in the field of bio-fuel production, biomass and energy, waste water treatment, compost and fertilizer, animal feed, furniture, with special focus to the application of water hyacinth for energy sector considering the fuel crisis and the urgency to go for the alternative way of utilizing energy are being discussed extensively in this review paper.

#### 4. Water hyacinth as alternative biomass resource for energy production

Today fossil fuel depletion and more toxic emission formation from combustion of fossil fuel have become the main concerns of energy and environmental societies [22]. The environmental dilemma problems such as climate change, receding of glaciers, increasing the sea level, GHG s effects and lack of biodiversity have been emerged due to lack of appropriate strategy to control the pollutant formation in transportation systems and industrial sectors [23]. Fossil fuels remain as the main source of energy. Recent production of fossil fuels has reached up to 79% compared to other energy resources as shown in (Fig. 1) [24]. However, the demand for fossil fuel as a primary energy source is exceeding its production, due to the rising consumption of fossil fuel energy up to 83% in November 2010.

Due to the population increase energy consumption will also increase in near future (Fig. 2) [24]. Achieving solutions to possible shortage in fossil fuels and environmental problems that the world is facing today require long-term potential actions for sustainable development. In this context, renewable energy resources appear to be one of the most efficient and effective solutions [1]. Bio-energy is now accepted and having the potential to provide

a major part of the projected renewable energy provisions required for future [2,3]. As projected in (Fig. 2), the energy related carbon dioxide emission will continue to gradually rise [24].

There are several reasons that drive most of the countries in shifting towards green energy production, which includes wind energy, solar energy, hydropower, biofuel and biomass. Most developed countries will focus on renewable energy that is more adaptable for them, for economical purposes, depending on the geographical location, climate condition and availability of renewable sources. For example, insolation (solar radiation) in the Mojave Desert near Barstow in California is good enough for photovoltaic activity and therefore suitable for solar power plants application [24]. In future, advanced biofuel produced from lignocellulosic biomass can replace biofuel produced from agricultural feedstock [25].

As aquatic plants do not compete with land resources used in arable food crop cultivation and thus are an incentive factor when it comes to biofuel production [26]. However, there are no exact figures available for bio-alcohol production from water hyacinth [27]. The energy crisis of 1970s renewed interest in alcohol production for fuels and chemicals. Ethanol is used in vehicles either as a sole fuel or blended with gasoline and with the growing energy crisis supplemented by environmental concerns, bi-methanation of water hyacinth can serve as a biomass-to-energy generation alternative. Water hyacinth management problems and environmental concerns as well as the on-going successful shifting from non-conventional to renewable energy technologies has given an impulse to focus on biogas production.

At present, much focus is on the development of methods to produce ethanol from biomass that possesses high cellulose content. This cellulosic ethanol could be produced from abundant low-value material, including wood chips, grasses, crop residues, and municipal waste. In the recent days, the cellulosic substrates searching has gained a new speed and is continuing, some of it includes water hyacinth, sunflower stalks, etc., which are being explored for ethanol production possibility in different laboratories [28].

The world ethanol fuel production for different continents, 2006–2011 [29] is shown in Table 1 and can be seen that America is dominant in the production of alcohol.

Generally, biofuel represents all of gaseous and liquid fuels mainly extracted from biomass. For example biodiesel, biomethanol, bioethanol and biohydrogen are extracted from biofuel [30]. The privileges of biodiesel not only have convinced governments to take biodiesel in account as an energy resource but also have pursued them to take new strategies to expand biodiesel production. Statistics illustrate that biodiesel production has risen drastically in recent years. Fig. 3 depicts world annual ethanol and biodiesel production from 2005 to 2020 respectively according to OECD and FAO Secretariats [31]. Also biodiesel, bio methanol, bioethanol and biohydrogen as main biomass products have been applied vastly in energy generation. Huge amount of biofuel resources, fluctuation in fossil fuel prices and environmentally friendly characteristics of biofuel combustion process have convinced the governments of tropical countries to invest in the development of biofuel industry [32,33]. It has been proven that the application of biodiesel blends mitigates the rate of CO<sub>2</sub> formation in industrial boilers dramatically [34].

For the development of alternative energy sources, the processing of agricultural wastes into biomass is an appropriate strategy. Water hyacinth is an aquatic plant which can be used as an alternative energy source to wood or other related briquettes. This aquatic plant was harvested, dried and ground into powder before being mixed with starch binder in manually operated briquetting machine. The briquettes produced were sundried and comparative cooking tests were carried out by burning the

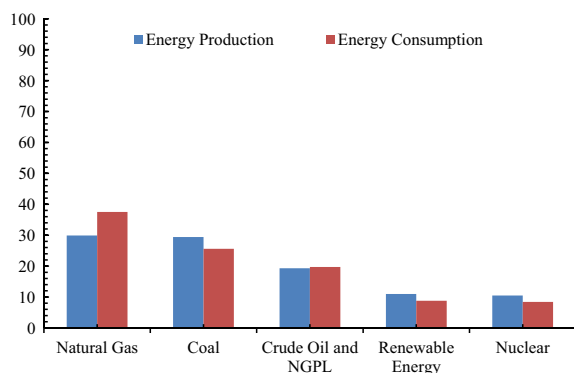


Fig. 1. World primary energy production and consumption in November 2010, per source [24].

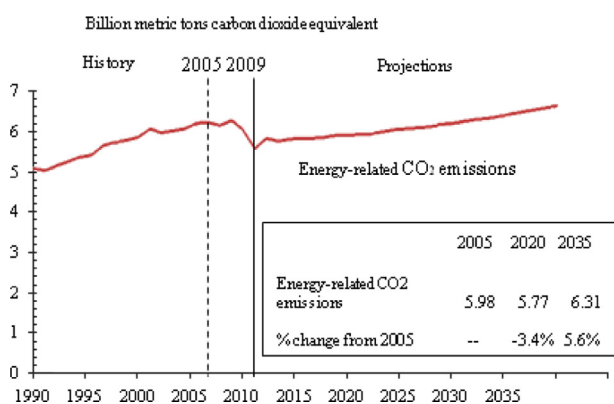


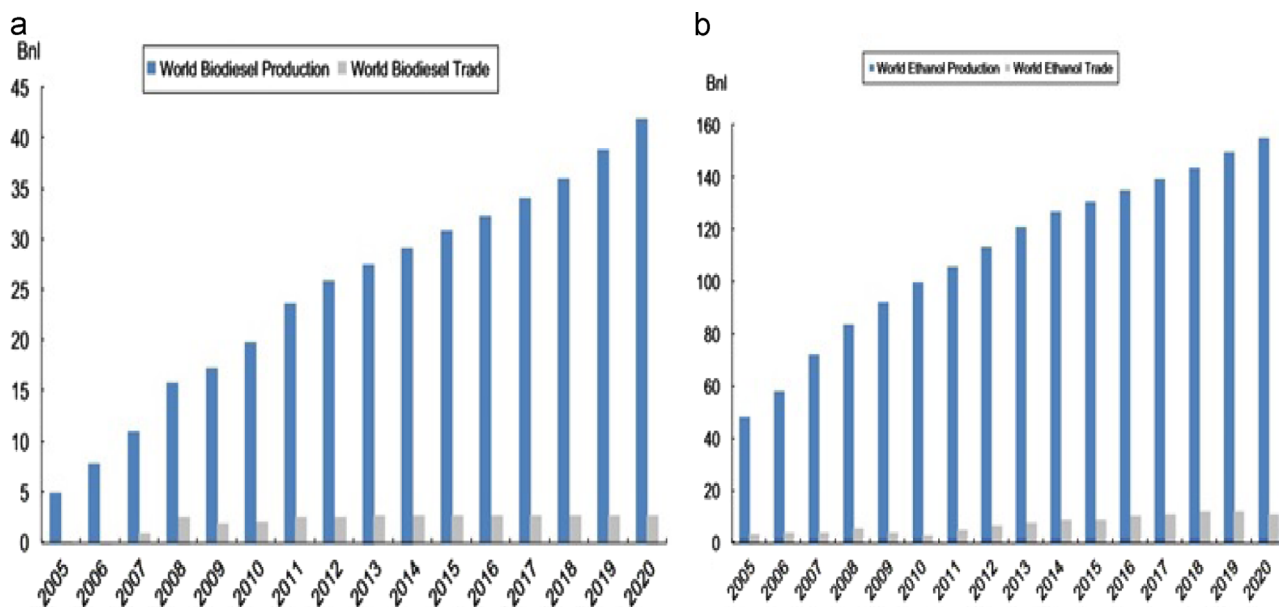
Fig. 2. U.S. energy-related carbon dioxide emissions from 1990 to 2035 [24].

**Table 1**

World ethanol fuel production (million liters).

Source: F.O. Licht (2011)

Region	Year					
	2006	2007	2008	2009	2010	2011
Americas	35,625	45,467	60,393	66,368	77,800	79,005
Asia/Pacific	1940	2142	2743	2888	3,183	4,077
Europe	1627	1,882	2,814	3,683	4,615	5,467
Africa	0	49	72	108	165	170
World	39,132	49,540	66,072	73,047	85,763	88,719

**Fig. 3.** World biofuel prediction (a) biodiesel and (b) ethanol [34].

briquette in a mold [35]. Forhadlne et al. [36] have shown the potential of biogas production using cow dung, poultry waste and water hyacinth through anaerobic digestion. These wastes are always available in our environment and can be used as a source of fuel if managed properly. Biogas technology can be a viable development option for developing countries for energy production and substitution if properly managed and marketed.

#### 4.1. Water hyacinth as co-fuel

Many researchers and scientists have attempted different kinds of fuels namely compressed natural gas (CNG), liquefied petroleum gas (LPG), hydrogen, and alcohols. The vegetable oils and alcohols (methanol and ethanol) are favorable renewable liquid fuels. Because of low cetane number, alcohols are not qualified for diesel engines. The poor volatility and low octane number make vegetable oils incompatible for spark ignition (petrol) engines. One possible solution to solve this problem is the use of bio-diesel. Two fuels which can be used as sole fuel or as mixture along with diesel fuel are: straight vegetable oil (SVO) and bio-diesel (which are esters of SVO) [37–41].

Water hyacinth satisfy all the criteria for bioenergy production – it is permanent, plenty available, non-crop plant, biodegradable and has high cellulose content; however its strong disadvantage is that it has over 90% water content which complicates the process of harvesting and processing. The biomass can be subjected towards biogas production as to generate energy for household use in rural areas [42]. Water hyacinth is low in lignin content (10%), contains high amount of cellulose (20%) and hemicellulose

(33%) [43–45]. Since a few decades, researchers have found its capability in fermentation process to generate biofuel and bio-ethanol. A typical biomass from land plants can have 30–50% cellulose, 20–40% hemicellulose and 15–30% lignin, which could hinder its capability in fermentation processes by selected commercial yeast and enzymes. In plants, lignin (composed of phenyl propanoid groups) acts as a polymer around the hemicellulose micro fibrils, binding the cellulose molecules together and protecting them against chemical degradation. Therefore, lignin compounds cannot be converted into sugars and may limit the capability microbiological activity during fermentation process. Therefore, some plants that contain higher lignin content are not useful for biofuel production. Their degradation involves high energy process. As water hyacinth has low lignin, the cellulose and hemicellulose are more easily converted to fermentable sugar therefore resulting in enormous amount of functional biomass for biofuel industry. As suggested by Poddar et al. [46] a new method of extracting ethanol from fermented sugar can be derived by saccharification technique, pretreatment with diluted sulfuric acid and further accelerate the fermentation process by using selected yeast extraction. In certain countries, water hyacinth is successfully utilized for biogas production at different fermentation capacities [47–49]. It is concluded that a mixture of 25% cow dung and 75% of dry water hyacinth could yield the best rate of methane production and specifies the huge potential of water hyacinth as non-conventional energy source with the anticipation that one-ton of dry water hyacinth could yield 370,000 L of biogas.

Considering the cost of various feed stock, to reduce the cost of fuel alcohol production, the use of water-hyacinth offers an

opportunity which is freely available in large amount as a substrate. The mixture of cow dung and water hyacinth slurry has proven to produce more biogas than when used alone [50]. The application of fuel ethanol (bioethanol) from biomass involves the step of pre-hydrolysis, hydrolysis, fermentation, and distillation. The hydrolysate resulting after pre-hydrolysis and hydrolysis include changeable amount of monosaccharide's, both pentose's and hexose's, and also a wide range of substances either obtained from the raw material or resulting as the reaction product from sugar and lignin degradation. Many of these compounds may have inhibitory consequence on microorganisms in subsequent fermentation steps [51–56]. The fermentation organism must be capable of fermenting all monosaccharide's present and in addition, survive potential inhibitors in the hydrolysate. The most normally used ethanol producer, *Saccharomyces cerevisiae*, cannot ferment pentose's, which may represent up to 40% of the raw material. Among the xylose fermenting yeasts *Pichia stipitis*, has shown promise for industrial application; because it ferments xylose quickly with a high ethanol yield and apparently produces no xylitol [57], and is able to ferment a wider range of sugars (including cellobiose) than *Candida shehatae* [58]. Also it has been demonstrated that the hydrolysate of water hyacinth biomass (WHB) can be fermented to ethanol using the common baker's yeast *Saccharomyces cerevisiae* albeit with lesser efficiency. The use of more suitable organisms for fermentation can improve the yield of ethanol. Almost all of the technologies that are employed in the production of bio-ethanol from WHB is less technically intensive and can be operated by non-skilled workers making the strategy suitable for small scale distributed production of fuel ethanol [59].

As shown in Table 2, recent studies have been carried out to optimize the operating parameters as well as the design and method of appropriate technology to convert water hyacinth into biofuel.

Many studies were conducted by pre-treatment processes, including acidification technique and numerous methods were developed for this purpose, including physical, chemical or biological processes. However, green ethanol is the preferred, ultimate raw alternative for energy and the best way is to apply biological processes for pretreatment and fermentation. The main issue in biological processes is their time consumption and in order to improve the biological limitation, researchers are currently modifying

biochemistry and bioprocess activities for the fermentation process. As biological processes are eco-friendly and lead to energy savings, one must carefully consider biological processes to preserve the environment and protect the planet which is increasingly under threat [4].

#### 4.2. Water hyacinth as briquette biomass (power plant energy)

Briquetting, also known as biomass densification of agro residues has been practiced in several countries for many years [68]. In the briquetting process, biomass residues will turn into uniform and solid fuel as briquettes which will enhance its properties with more added values. This biomass briquette has the characteristic of higher density and energy content besides having less moisture content compared to their raw materials [69]. Among the commercial biomass briquettes are sawdust briquettes, wood residues and rice husk briquettes which are available in the local market [68,69]. In Kenya, the purpose of briquetting is to deal with the massive growth of water hyacinth and is expected to benefit the lake side communities. As water hyacinth is the fastest growing plant, thus its biomass has the potential to become the renewable energy source in replacing conventional fossil fuel [70].

Biomass waste material is usually very bulky and has a very low density which makes it very difficult to be used in many types of burners and transportation is also very uneconomical [71]. Densification of biomass is one of the solutions to this problem. Briquette quality is evaluated mainly by the briquette density [72]. If produced at low cost and made conveniently accessible to consumers, briquettes could serve as complements to firewood and charcoal and kerosene for domestic cooking and agro-industrial operations, thereby reducing the high demand for them. Besides, briquettes have been noted to have advantages over fuel wood in terms of greater heat intensity, cleanliness, convenience in use, and relatively smaller space requirement for storage [73]. A number of locally available materials have been found to be suitable for briquetting into fuel energy production. These include sawdust, cowpea chaffs, corn cobs, and water hyacinth [74].

Wide development of industrial sectors often results in creating a polluted environment. The availability of coal leads to increased use of fossil fuels worldwide. Easy access to electricity is the basis of higher living standard. As in United States, coal-fired

**Table 2**  
Biogas production from various studies using water hyacinth.

Reference	Summary/methods of application	Results/findings
[60]	Pretreatment with fungi or chemicals to increase the biodegradability of water hyacinth.	Untreated water hyacinth: 0.10l g <sup>-1</sup> dm; <i>Phanerochaete chrysosporium</i> pretreatment: 0.24l g <sup>-1</sup> dm; pyrogaliol red + <i>P. chrysosporium</i> : 0.31l g <sup>-1</sup> dm.
[61]	Water hyacinth + night soil (1:3 and 3:1).	Increased biogas production, rich in CH <sub>4</sub> .
[62]	Investigation of, both experimentally and theoretically using mathematical tools, a fermentative system utilizing water-hyacinth hemicellulose acid hydrolysate as a substrate for ethanol production using <i>Pichia stipitis</i> .	Xylose (72.83%) converted to ethanol with a yield of 0.425 gp/gs and productivity of 0.176 gp/L/h.
[59]	Suitability of feedstock for production of fermentable sugars using cellulase produced on site and testing of acid and alkali pretreatment methods.	Enzyme blends resulted in improvement of saccharification from 57% to 71% with <i>Saccharomyces cerevisiae</i> .
[63]	The mild acid pretreatment and combination of biological pretreatment by white rot fungus <i>Echinodontium taxodii</i> or a brown rot fungus <i>Antrodia sp.</i> 5898 with mild acid pretreatment were evaluated.	Ethanol yield from co-treated water hyacinth achieved 0.192 g/g of dry matter, which increased 1.34-fold than that from acid-treated water hyacinth (0.146 g/g of dry matter).
[64]	Two-sequential steps of acid hydrolysis (10% sulfuric acid) and yeast ( <i>Candida shehatae</i> ; xylose-fermenting yeast) used for bioconversion of water hyacinth to liquid ethanol.	Maximum ethanol yield coefficient of 0.19 g g <sup>-1</sup> WH with the productivity of 0.008 g l <sup>-1</sup> h <sup>-1</sup> achieved.
[65]	The acid pretreatment and enzymatic hydrolysis was used to ferment sugar to ethanol. Hydrolysis and fermentation (SHF) studies were carried out separately to produce ethanol from water hyacinth leaves.	Ethanol concentration of 3.39 (g/l), percentage of theoretical ethanol yield of 96.07%, ethanol yield of 0.25 g/g and the volumetric productivity of 0.221 g/l h obtained.
[66]	The effect of physical (subcritical water) and chemical (acid and alkali) pretreatment on conversion of lignocellulose (cellulose, hemicellulose) in water hyacinth (WH) was investigated.	Combination of acid or alkali pretreatment with enzyme treatment resulted in drastic increase of sugar in samples (up to 31.2 and 22.9%) w/w, after fermentation, up to 60% of sugar in the sample converted to ethanol.
[67]	The optimization of pretreatment process was conducted for the enzymatic hydrolysis of lignocellulosic biomass (water hyacinth).	The order of catalytic effectiveness for hydrolysis yield was found to be phosphoric acid > maleic acid > sulfuric acid.

**Table 3**  
Briquette production from water hyacinth.

Reference	Summary/methods of application	Results/findings
[35]	Comparison of cooking time obtained were made along with the time obtained, when same quantities of food were cooked using a conventional kerosene stove.	Use of water hyacinth briquette took longer time for cooking purpose, when compared to kerosene stove. Water hyacinth biomass can serve as an alternative energy source.
[91]	Assessment of electric power generation using water hyacinth (WH) and agricultural waste.	Produced electricity ranging from 1.38 to 1.41 kWh/m <sup>3</sup> . 1 t of WH can produce average 13.3 m <sup>3</sup> of biogas and 18.35–18.75 kWh electricity
[86]	Effect of compaction pressure, binder proportion, particle size on ignition time and burning rate of fuel briquettes produced were carried out with the mixture of water hyacinth and plantain peel.	Compaction pressure and binder proportion caused decrease in burning rate.
[92]	Quality of fuel briquettes made from sewage sludge mixed with water hyacinth was investigated.	Highest calorific value of (3362.9 cal/g) was obtained at 1:3 ratio and provided highest compressive strength value of (4545 N).
[89]	Assess the combustion characteristic of briquettes produced from mixed water hyacinth and plantain peels as binder, mangrove wood, charcoal and <i>Anthonotha macrophylla</i> (firewood).	The results confirm the possibility of utilizing water hyacinth as fuel briquettes as good source that can support combustion, to provide high material strength as well as high value of combustible fuel.
[93]	Use of water hyacinth briquettes as alternative to the locally available wood fuel.	Water hyacinth briquette has greater amount of moisture content, similar amount of volatile matter, and much greater ash content, significantly much less fixed carbon and much lower calorific value when compared to the local wood fuel.

power plants generate half of the electricity [75]. This fact greatly contributes towards the environmental problem related to the emissions of SO<sub>2</sub>, NO<sub>x</sub> and greenhouse gas (CO<sub>2</sub>) from the activity of co-firing coal. Thus, co-firing biomass with coal in the existing coal fired boilers will reduce the emission of greenhouse gases [76]. In their research it was found that the co-firing woody biomass and bituminous coal with the proportion of 60:40 showed great reduction of SO<sub>2</sub>, NO<sub>x</sub> and suspended particulate matter (SPM) as compared to co-firing bituminous coal alone. Unfavorable emissions can be reduced up to 15–20% by partial combustion of biomass and coal in the existing pulverized coal-fired boilers [77]. Biomass co-firing can reduce the share of emissions per unit energy produced [77] with small capital investment as compared to single coal firing [78].

The best selection of raw material for briquetting is based on their moisture content, ash content, flow characteristic and particle size. Most of biomass residues possess lower ash content, but at the same time they have higher potassium content which tends to devolatilize during combustion and become condensed on superheated surfaces [68,79]. Thus, it does not mean that biomass with lower ash content will not show any slagging behavior even though in general, biomass with greater ash content would form great slagging behavior [68]. In one study, [80] it is found that there was no significant difference in terms of calorific value between charcoal briquette from water hyacinth and mixture of charcoal including water hyacinth powder. Many researchers have reported on the combustion properties of briquettes fuel for various agricultural waste products such as charcoal briquettes from neem wood residue [81]. Also, production of fuel briquettes from waste paper and coconut husk [82], rice husk and saw dust [83], composite sawdust briquettes [84], palm kernel briquettes [85] and mixture of water hyacinth and plantain peel [86].

As stated by [87], biomass briquetting can enhance the agro residues characteristic for feeding into furnaces and combustion. While [88] suggested that less compact form of agro residues which are transforming into briquettes form is technologically more efficient when compared to direct firing. It is also reported by [88], that 67% of the total energy consumption in India consists of coal. Besides, higher production of ash (low calorific value), a need to low cost transportation and bad environmental impact were the main reasons for India to substitute coal into briquetting, also because of its abundant agricultural residues. Rotimi et al. [89] demonstrated the use of briquettes produced from water hyacinth to be considered as environmental friendly and to reduce health hazard associated with the use of fuel-wood and charcoal.

Furthermore, when a piece of wood was mixed into briquette it showed greater expansion in cooking time. This suggests that water hyacinth biomass in the form of briquette can be used as charcoal substitute for industrial purposes. Among the third world countries, India is the only country that has successfully developed their briquette sector [68]. As discussed by Emerhi [90], it was found that a charcoal and sawdust based briquette can produce a hot, smokeless and longer time of fire. Table 3 shows some recent studies of using water hyacinth as fuel briquette, charcoal substitute and electric power generation.

## 5. Other applications

### 5.1. Wastewater treatment (phytoremediation)

Harvesting aquatic plants to withdraw nutrients from waste water is one of the early methods to reduce pollution in lakes. It is pointed out that all aquatic plants can serve this purpose. However, small plants, like phytoplankton, or submerged plants are more difficult and expensive to harvest than the floating and emergent vascular plants [94]. Water hyacinth has the ability to clean up various contaminated waters [95–97]. In the past decades, the application of Waste Stabilization Pond (WSP) has attracted attention to treat swine effluent. Both laboratory and field studies shows that water hyacinth is able to reduce a variety of pollutants present in the swine wastewater [98]. Numerous researchers [99–101], have tested *Eichhornia crassipes*, *Pistia stratiotes*, *Salvinia rotundifolia* and *Lemna minor* and found that water hyacinth (*E. crassipes*) has greater capacity of nitrogen and phosphorus removal. Phosphorus pollution in aquatic environment is generally recognized to be from three major sources: industry, agriculture and domestic sewage [102]. *E. crassipes* has been known to support its growth contaminated water because of its settlement action and absorption capacity. The high productivity rate of water hyacinth is one of the most important reasons why it has been universally used in Southern France for the treatment of industrial waste waters [103]. As mentioned by Williams [104] the efficiency of nitrogen removal rate is from 10 to 90%. Also research over the past few decades has demonstrated that some floating plants, such as water hyacinth (*E. crassipes*), water lettuce (*Pistia stratiotes*), pennywort (*Hydrocotyleum bellata*), duckweed (*Lemna minor*), water peanut (*Alternantheraphiloxeroides*) and lidded cleistocalyx (*Cleistocalyx operculatus*), have the greatest effects on purifying eutrophic water [105–107]. Therefore, water hyacinth

and duckweed were tested in the treatment of pig and dairy manure-based wastewater [15,108].

### 5.1.1. Removal of organic pollutants

Among the floating aquatic plants, water hyacinth has been extensively studied at laboratory, pilot and larger scale for removing the organic matter present in wastewater [109]. Even though water hyacinth is a persistent plant in most of the countries all over the world; it is also being used as a resource in agricultural and waste management process [20]. As estimated by Wu et al. [110], the practical use of water hyacinth grown in natural water channels or ponds is mainly for water purification. They suggested shorter harvesting intermission to obtain more yield of the biomass. As indicated by [111] in the treatment of dairy wastewater, water hyacinth was discovered to be more effective. The wastewater was treated with water hyacinth for a period of 25 days and various physio-chemical parameters were analyzed according to the series of treatment. After 25 days, total solids, calcium, magnesium and total hardness were reduced by 37, 5, 47.5, 54 and 33%, respectively. Water chloride, chromium, nitrous nitrogen, nitric nitrogen, pH, alkalinity, COD, BOD, bicarbonates were also reduced considerably. This phytoremediation technology is suitable in treating industrial wastewater since it can be used to treat contaminated soils, groundwater and wastewater in both low cost application and technology [112].

As reported by Jayaweera et al. [113], water hyacinth growth under the different nutrient conditions for Fe enriched wastewaters in batch-type constructed wetlands have been studied base on phytoremediation efficiencies. At the 6th week with a highest accumulation of Fe, 67 mg/kg dry weights, the obtained results showed the highest phytoremediation efficiency of 47% during optimum growth. Table 4 shows the some recent studies about application of water hyacinth for treatment of any type of waste water.

### 5.1.2. Removal of toxic pollutants and heavy metals

With global heavy metal contamination on the rise, plants that can process heavy metals might provide efficient and ecologically sound approach to sequestration and removal [119–121]. The phytoremediation of metals is a cost-effective green technology based on the use of metal-accumulating plants to remove toxic metals,

including radionuclide, from soil and water. Phytoremediation takes advantage of the fact that a living plant can be considered as a solar-driven pump, which can extract and concentrate particular elements from the environment [115]. The root of the plant will be absorbing the metal pollutant that restrain in the wastewater and enhance the quality of water [15]. Water hyacinth has drawn attention as a plant capable of eliminating pollutants, including toxic metals from surface water. Reduction of heavy metals in situ by plants may be a functional detoxification mechanism for phytoremediation. Numerous studies were conducted to determine the phytotoxic effects and uptake capacity of heavy metals by water hyacinth [64,122–124].

Aquatic macrophytes have frequently been used to monitor freshwater pollution by heavy metals and pesticides. In tropical and subtropical regions, because of its abundance and the large biomass produced, the water hyacinth (*Eichhornia crassipes*) has been studied especially for this purpose. The ecology and the practical use of this species were comprehensively revised by Delgado et al. and Klumpp et al. [125,126].

The root structures of water hyacinth (and other aquatic plants) supply an appropriate environment for aerobic bacteria to function in sewage systems. Aerobic bacteria feed on nutrients and produce inorganic compounds which in turn provide food for the plants. To prepare rich and valuable compost, the plants grow rapidly and can be harvested. Water hyacinth has also been used for the removal or reduction of nutrients, heavy metals, organic compounds and pathogens from water [1].

Water hyacinth is not only capable to absorb and accumulate heavy metals, but also it can tolerate toxicity by converting it from chemically-active toxic status to inactive and nontoxic status. For example, [90] estimated the removal of chromium (III) from aqueous solution by water hyacinth. The results proved chromium removal rate at 10 mg Cr/l solution, which the recovery was monitored at 87.52%. However in higher concentrations (e.g. 50 or 100 mg/l), the water hyacinth response in a weak performance that concluded higher ratios of water hyacinth mass/solution volume lead to higher solution decontamination. The absorption of Cr (III) by water hyacinth was lowered by decreasing the pH solution. The Cr (III) removal by water hyacinth was not influenced by the temperature in the range 17.5–26.0 °C or by the dissolved oxygen concentration in the solution between 4.7 and 6.8 mg/l.

In a study in Dhaka, Bangladesh, Water hyacinth plants from a pond were dried in air and a fine powder was prepared from the

**Table 4**  
Phytoremediation of nutritionally rich wastewater by water hyacinth.

Reference	Wastewater source	Main pollutants	Results	Comments
[109]	Piggery wastes (tertiary treatment)	COD, BOD, TN, TP	50% reduction in all parameters at 110 kg TN/ha/d and 20 d HRT	Use of harvested WH as animal diet
[114]	Sewage treatment	Metals, BOD, nitrates and phosphates	Removal of metals (20–100%) BOD (97%); nitrates and phosphates (> 90%)	Combination of WH, duckweed and blue-green algae
[115]	Dairy effluent	Nitrogen and phosphorus	Removal of N (72%) and P (63%)	Combination of WH and Duck weed gave N (79%) and P (69%) removal
[15]	An aerobically digested flushed dairy manure wastewater (1:1 dilution)	Total nitrogen (TN), total phosphorus (TP), NH <sub>4</sub> <sup>+</sup> , EC, Na <sup>+</sup>	Reduction (%) of TN (91.7), NH <sub>4</sub> <sup>+</sup> (99.6), TP (98.5) coupled with reduction in EC and Na <sup>+</sup>	WH gave best performance While poly culture (of 3 spp.) ranked 2nd
[116]	Duck farm	COD, TP, TN,	COD removal 64.44 (%) TP removal 23.02 (%) TN removal 21.78 (%)	Remarkable removal from duck farm
[117]	Swine wastewater	Nitrogen and phosphorus	The adsorption efficiency was about 36% upon saturation	Shown much greater NH <sub>3</sub> -N reduction efficiency
[118]	Fish farm wastewater	pH, turbidity, (DO), (COD), (BOD), nitrite phosphate (PO <sub>4</sub> <sup>3-</sup> ), nitrate (NO <sub>3</sub> <sup>-</sup> ), nitrite (NO <sub>2</sub> <sup>-</sup> ), ammonia (NH <sub>3</sub> ), and total kjedahl nitrogen (TKN)	pH ranging from 5.52 to 5.59 and from 4.45 to 5.5, reduction of turbidity were 85.26% and 87.05%, similar reductions were observed in COD, TKN, NO <sub>3</sub> <sup>-</sup> , NH <sub>3</sub> , and PO <sub>4</sub> <sup>3-</sup>	Removal of aquatic macrophytes from water bodies is recommended for efficient water purification.

**Table 5**  
Uptake of some heavy metals by water hyacinth.

References	Type of heavy metal removal	Findings	Comments
[131]	Arsenic, chromium, mercury, nickel, lead, zinc	Six different concentrations ranging from 5 mg/l to 50 mg/l were studied. It was observed that in aqueous solutions containing 5 mg/l of arsenic, chromium and mercury the maximum uptake were 26 mg/kg, 108 mg/kg and 327 mg/kg of dry weight of water hyacinth respectively.	At lower concentrations (5 mg/l) of heavy metals, the plant growth was normal and removal efficiency was greater.
[132]	Cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), and nickel (Ni)	The concentrations in the root tissue were found in the order of $Cu > Zn > Ni > Pb > Cd$ . The absorption capacity for water hyacinth was estimated at 0.24 kg/ha for Cd, 5.42 kg/ha for Pb, 21.6 kg/ha for Cu, 26.2 kg/ha for Zn, and 13.5 kg/ha for Ni.	Translocation ability was defined as the quantity of Cu, Pb, Cd, Ni, and Zn translocated in the plant's tissues and expressed as a root/shoot ratio.
[133]	Cadmium (Cd) and zinc (Zn)	Highest concentration of metals in roots (2040 mg/kg for Cd and 9650 mg/kg for Zn). However, relatively little Cd (113 mg/kg) was translocated to the shoot, while Zn was translocated at a much higher concentration (1930 mg/kg).	This result demonstrated that Zn was much more mobile than Cd.
[134]	Chromium,	Water hyacinth has tremendous potential to absorb heavy metals from the textile wastewater as it resulted in 95% reduction of chromium,	ANOVA analysis showed a significant ( $p < 0.05$ ) reduction in pollutants with the passage of time, especially in textile industry wastewater.
[128]	zinc, copper Arsenic	97% in zinc and 94% reduction in copper. The amount of arsenic remaining in solution was found to be less than	Removal of arsenic solution concentration of 1500 mg l <sup>-1</sup> , approximately 30 g of dried roots were required to remove 1500 mg of arsenic from 1 l of water in 24 h.
[135]	(Cd <sup>2+</sup> ), (Cu <sup>2+</sup> ), (Pb <sup>2+</sup> ), (Zn <sup>2+</sup> )	10 kg <sup>-1</sup> which is the WHO guideline limit value for As in drinking water. The equilibrium data were correlated with Langmuir and Freundlich Isotherm models. Based on the Langmuir model the maximum adsorption capacities were found to be 3.2, 18, 16 and 13 mg/g for cadmium, copper, lead and zinc respectively.	Maximum removal of metal ions took place at pH 4–6.

roots. From a solution containing 200 g of arsenic per L within 60 min of exposure to the powder, more than 93% of arsenite and 95% of arsenate were removed. The arsenic concentration remaining was less than the WHO drinking water guideline value of 10 g/L. Earlier Misbahuddin and Fariduddin [127], had noted that water hyacinths removed arsenic when placed in arsenic contaminated water for 3–6 h. The extent of arsenic removal depended on the arsenic concentration present, the amount of water hyacinth used, the exposure time and the presence of air and sunlight. Also Shaban et al. [128] reported that whole plants were more effective in removal of arsenic compared to fibrous roots alone.

Also water hyacinths (*E. crassipes*) were used as a pollution monitor for the simultaneous accumulation of arsenic, cadmium, lead and mercury [129]. The plants were harvested and rinsed with tap water after 2 days of cultivation in tanks containing 10 ppm each of As, Cd, Pb and Hg in aqueous solution. Also for each type of metals, the leaves and stems were separated and analyzed. The ratio of the arsenic and mercury concentrations in the leaves to that of the concentrations in the stems was found to be 2:1. Cadmium and lead showed a concentration ratio of about 1:1 in the leaves versus the stems. At 0.3 mg/g of dried plant material, the arsenic concentration in leaves was the lowest of all the metals. The leaf concentration of cadmium was highest at 0.5 mg/g of dried plant material. Arsenic removal by water hyacinths (*E. crassipes*) was also reported by Low and Lee [130]. Table 5 shows some recent studies about uptake of some heavy metals by water hyacinth for treatment of any type of waste water.

## 6. Composting and fertilizer

Water hyacinth can be used in farming as an organic fertilizer and as a mulch crop. There has been an increase in demand for organic foods, particularly in the developed world. The plant also contributes to protect soil moisture and nutrient recuperation. The plants can be turned into compost and used as a fertilizer. The

plant tends to retain most of the nutrients at a dry condition [136]. The time taken in composting is only 30 days compared to other crop plants, which can take up to 2–3 months [137].

The water hyacinth can be used on the land either as surface mulch or as compost. Mulching field crops with water hyacinth was found to increase the production of lady finger (67%), potato (14%) and tomato (90%) as compared to control (no mulching) treatment [138,139]. However Lenzi et al. [140] observed that mulching with water hyacinth when treated with maximum rates of glyphosate, and 2,4-D herbicides reduced growth of tomato as compared to untreated water hyacinth when used as mulch. Therefore, while using water hyacinth for mulching or composting purpose more intensive care is required such as not to spray with herbicides. Predictable composting, which is suitable for labor intensive, low capital production can be done by mixing dried plant with ash, soil and some animal manure/organic municipal waste. Vermicomposting of water hyacinth is more valuable because the water hyacinth losses its capability to reproduce vegetatively after it has passed through the earthworm gut [141].

The biomass of water hyacinth can be used directly as green fertilizer as compost. Furthermore the assimilated vegetative waste from biogas generation as specified above can also be collected for using it directly on the farm. Otherwise, these materials could be mixed with other organic materials before use. The crude powder obtained from the root of water hyacinth has successfully been used to support crop production in economic crops such as vegetables [142]. As mentioned by Oguniade et al. [143] water hyacinth can be rich in nitrogen, up to 3.2% of DM and have a C/N ratio around 15. Also Water hyacinth, due to its abundant growth and high concentrations of nutrients, has a great potential as fertilizer for the nutrient deficient soil.

## 7. Animal feed (livestock)

The lack of animal protein with increasing cost of food production coupled with rapid population growth demanded the

search for non-conventional sources of protein such as leaf protein concentrate (LPC) from water hyacinth [144]. This plant in arrangement with concentrate of other feeds has established to be a good quality protein source for animal feed [145]. The high water and mineral content of water hyacinth indicates that the nutrients in water hyacinth are appropriate to some animals as feed [142]. Boiled and chopped water hyacinth along with vegetable waste, rice bran, copra cake and salt is used to make suitable feed for pigs in China. When the plant is sun-dried, it has been found to be rich in protein, vitamins and minerals and serves as a high quality feedstock for some non-ruminant animals, poultry and fishery in Indonesia, China, the Philippines and Thailand [146,147].

In Malaysia, Indonesia, Philippines and Thailand the water hyacinth is used as feed for pigs, ducks and fish [148]. As indicated by Oguniade et al. [143] because its dry matter has high crude protein (18%) and low acid detergent fiber (33%) contents the water hyacinth has potential as a roughage source for ruminants. It is also reported that when grass crop (*Ctenopharyngodon idella*) were fed diets containing from 0 to 100% water hyacinth meal, weight gain and protein efficiency ratio decreased as the amount of water hyacinth meal increased. Water hyacinth has also been used indirectly to feed fish. Dehydrated water hyacinth has been added to the diet of channel catfish fingerlings to increase their growth [149]. It has also been noted that decay of water hyacinth after chemical control releases nutrients which promote the growth of phytoplankton with subsequent increase in fish yield [127]. The effects on egg quality with water hyacinth as duck feed (cattle feedstock), eggshell thickness and intensity were evaluated based on statistical analysis [116]. As well as encouraging digestion and absorption in the ducks, water hyacinth is rich in protein and minerals, especially calcium, which reached 2.0% of dry matter, and thus it could increase the eggshell strength. Because the experimental and control groups had the same eggshell relative weights, this specified that adding water hyacinth to the diet increased egg weight and consequently increased the eggshell weight [150].

## 8. Furniture

Water hyacinth can be used for furniture-making. So far it has not been figured out by any other researchers for academic matters even though commercial products have been developed in India, Thailand, China and Indonesia. Since no other researcher utilizes their potential previously, the furniture-making from water hyacinth is a novelty research. Using water hyacinth for furniture making is still difficult due to the higher material quality demand and difficulty of process making. However, as discussed by Jafari [19], biomass can be turned into durable, esthetic furniture and handicrafts professionally. In the Philippines, this weed is dried and the stalks are weaved into baskets and mats. Also, in India, similar domestic goods are manufactured from this weed such innovative decorative articles are known among visitors.

## 9. Conclusion

By referring to the latest research on the water hyacinth has promoted our awareness about the basic as well as applied characteristics of this plant. This information will help to develop any future utilization of water hyacinth. A suitable large-scale utilization could supply as a positive advance to control the spreading of the water hyacinth. The paper has discussed the adaptability of the water hyacinth to deal with domestic/industrial

wastewaters of various origin and nature and shown the efficiency of this plant for removal of pollutants from wastewater. The water hyacinth can also serve as an alternative source of energy.

According to literature, the most and beneficial usage of water hyacinth is biofuel production, mainly in Brazil, India and some African countries. It is found that 1 kg of cellulose yields 1.1 kg of glucose and 1 kg of cellulose yield 0.56 kg of ethanol.

Other consumption options including water hyacinth-based power plant energy, compost/fertilizer and animal feed production also make the engineering feature important in many commercial ways. The focus on future outlook should be power plant energy. It can help to decrease the use of fossil fuels. The use of water hyacinth in developing countries for animal feed may help solve some of the nutritional limitations in these countries. Treating the presence of abundant water hyacinth and using its significant heat content as an ideal opportunity to sensitize local communities for serving it as alternative biomass with economic and environmental advantages will be an added value.

The new idea can be to use the plant for several purposes at the same time. For example, after water hyacinth phyto-remediation and uptake nutrient from waste water, the biomass can be used in power plant energy or biofuel production. However, until now the utilization has not developed into large scale activities other than localized cottage industries or to support poor communities in subsistence continuations such as the production of biogas. Government could further break the barrier and provide means to educate people about usage of this non-fossil source of energy and also support the scientific research to further explore the plant potential.

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